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THE EFFECTS OF TRACKING STATION COORDINATE UNCERTAINTIES ON GEOS-II ORBITAL ACCURACY

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Greenbelt, Maryland

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ABSTRACT

Laser and Minitrack observational data from GEOS-II collected during the period April 23, 1971 to May 21, 1971, have been used for the purpose of assessing the influence of tracking station location on the accuracy of orbit determination. These data were processed using a unified set of coordinates for the tracking station locations. Concurrently, these data were processed using non-unified station locations referred to a variety of geodetic datums. The resultant orbits based on the two different sets of station locations were compared and relative differences in the position of the satellite were determined. Differences between the two groups of orbits fitted over four-day data spans ranged from 250 meters to 500 meters for orbits derived from laser data only. For orbits observed from Minitrack data alone the relative differences in GEOS-II spacecraft position ranged from 50 meters to 190 meters.

The entire span of data was divided into a sequence of eleven four day long arcs, overlapping each other by two days. Utilizing the laser data alone in each arc, definitive orbits were computed using the unified and non-unified station location coordinates. The differences in the satellite position in the overlap region when using the unified laser station coordinates ranged from 25 meters to 150 meters, whereas when using the non-unified laser station coordinates the differences in position ranged from 180 to 650 meters. These differences in the position vector as described above were consistently observed.

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THE EFFECTS OF TRACKING STATION COORDINATE UNCERTAINTIES ON GEOS-II ORBITAL ACCURACY

1.0 INTRODUCTION

The purpose of this study was to evaluate and compare the effects of tracking station location uncertainty on GEOS-II orbital accuracy. The study involved the comparison of orbits derived from the same tracking data but using two different sets of tracking station coordinates. One set being the coordinates for tracking stations referred to a common center of mass system (i.e., SAO Standard Earth 1969, Reference 1), and the other set of station coordinates were referred to a variety of geodetic datums. Both sets of the station coordinates used were obtained from a GSFC report by J. G. Marsh, B. C. Douglas, S. M. Klosko, "A Unified Set of Tracking Station Coordinates Derived from Geodetic Satellite Tracking Data," Reference 2.

The two types of tracking data used for orbit determination were laser-range and Minitrack-direction cosines respectively. The resulting orbits were compared in both the direct-arc, and the overlapping-arc sense.

2.0 TECHNICAL APPROACH

2.1 Methods of Arc Comparison

For this study, two methods were used to evaluate the accuracy of the orbit determination results.

(1) The direct-arc comparison involves obtaining the differences between the satellite position vector components for two orbital arcs with identical observational data but computed using the two different sets of station coordinates.

(2) The overlapping-arc comparison involves obtaining the differences between satellite position vector components at identical times for two overlapping orbital arcs computed with the same set of station coordinates.

In practice, an orbit is fitted in the least squares sense to data over a specified time span. Upon convergence of the differential correction process, a set of orbital parameters is obtained along with the RMS error of fit. Using this set of orbital parameters, an ephemeris is generated, which is used either for comparison in the overlap region with the next ephemeris arc, or for comparison with another ephemeris corresponding to the same time period and observations, but with the different tracking station coordinates.

2.2 Overlap Procedure

In this study, the following scheme was used to construct the orbital arcs and the overlap intervals. Define the length of time span of an orbital arc to be

$$t_L = \text{E. T.} - \text{S. T. (end time - start time)}.$$

The epoch was chosen to be at the midpoint of this time span. Succeeding arcs were of the same time length and such that the start time of consecutive arcs correspond to the epoch or midpoint of the preceeding arc. This procedure is presented schematically below (Figure 1).

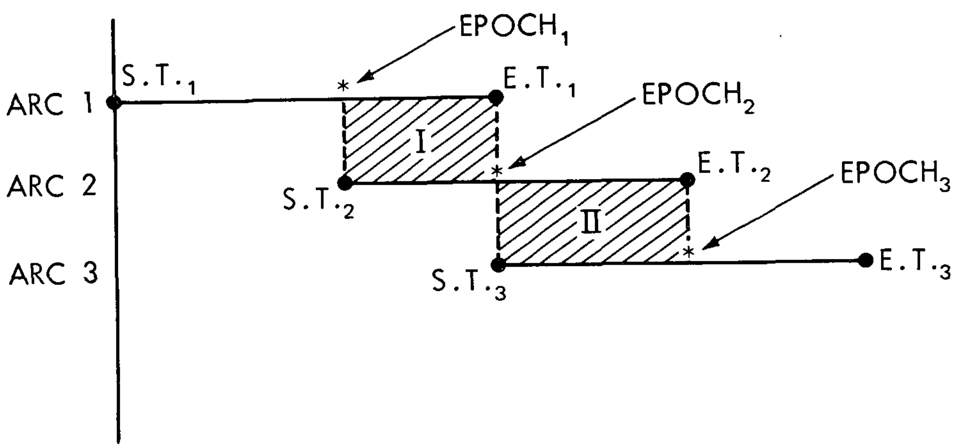


Figure 1. Schematic Representation of Orbital Arcs and Overlap Regions

Thus, the overlap interval between arc 1 and arc 2 is represented by the shaded area I, the overlap interval between arc 2 and arc 3 is represented by the shaded area II, and so forth. The observational data in this overlap interval were used twice to compute two successive orbits, and the overlapping portion of the orbits were compared by obtaining the satellite position vector component differences at identical times (see Reference 3).

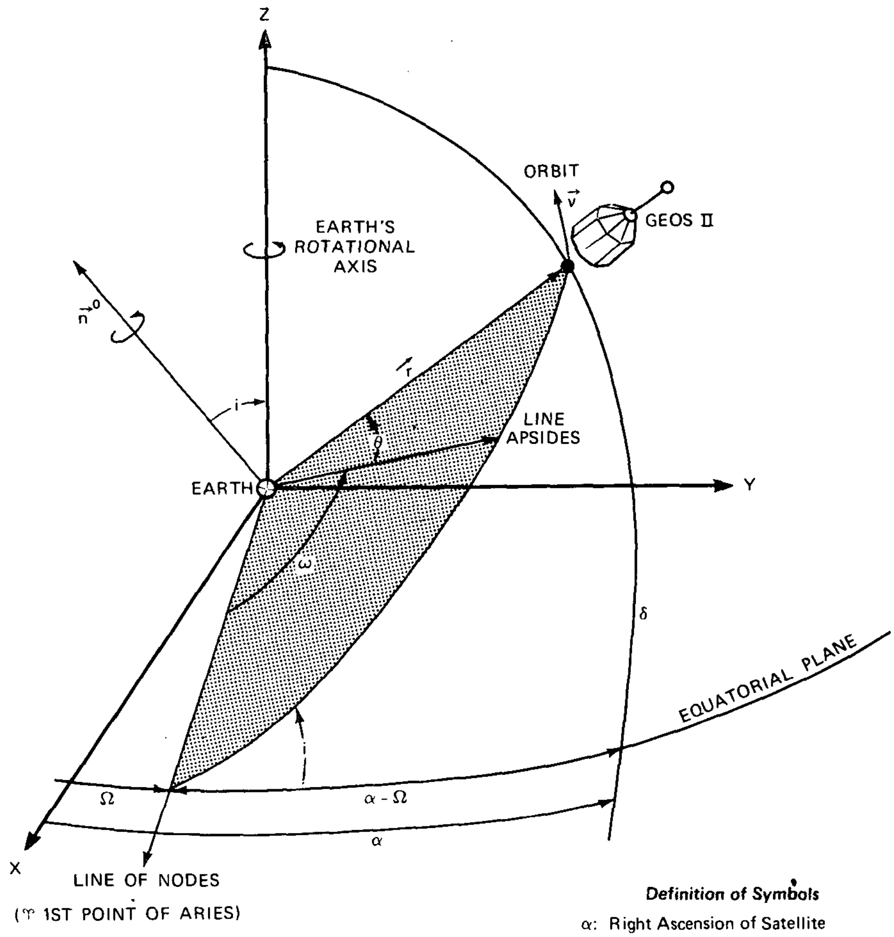
The coordinate differences between the three satellite position vector components for successive orbital arcs in this overlap interval are designated as the Orbital Uncertainty Estimates (OUE). The OUE's represent a measure of orbit consistency. The three components computed are:

(1) The radial component

(2) The cross-track component

(3) The along-track component.

Figure 2 provides an illustration of these three components.



INERTIAL COORDINATE SYSTEM

X-AXIS DIRECTED TOWARDS ARIES
Y-AXIS NORMAL TO X, Z AXES
Z-AXIS DIRECTED ALONG EARTH'S ROTATIONAL AXIS

Definition of Symbols

α: Right Ascension of Satellite

δ: Declination of Satellite

Ω: Right Ascension of Ascending Node of Satellite

ω: Argument of Perigee of Satellite

i: *Inclination of Satellite Orbit Plane to Equatorial Plane*

θ: True Anomaly

$\vec{r}$ = POSITION VECTOR OF SATELLITE

$\vec{v}$ = VELOCITY VECTOR OF SATELLITE

$\vec{n}^0 = \dfrac{\vec{r} \times \vec{v}}{|\vec{r} \times \vec{v}|}$: UNIT VECTOR IN CROSS TRACK DIRECTION

$\vec{h}^0 = \left(v^2 - \dfrac{(\vec{v} \cdot \vec{r})^2}{r^2}\right)^{-\frac{1}{2}} \left[\vec{v} - \dfrac{\vec{v} \cdot \vec{r}}{r^2}\,\vec{r}\right]$: UNIT VECTOR IN ALONG TRACK DIRECTION

$\vec{r}^0 = \dfrac{\vec{r}}{|\vec{r}|}$: UNIT VECTOR IN RADIAL DIRECTION

$\vec{v}^0 = \dfrac{\vec{v}}{|\vec{v}|}$: UNIT VELOCITY VECTOR

$\vec{v}_R = \dfrac{\vec{v} \cdot \vec{r}}{r}\,\dfrac{\vec{r}}{r} = \dfrac{\vec{v} \cdot \vec{r}}{r}\,\vec{r}^0$: RADIAL VELOCITY VECTOR

Figure 2. Description of Spacecraft Geometry

2.3 Computation Parameters

The computations for this study were performed with the NONAME Orbit Determination Program (Reference 4). All inputs to the NONAME program remained unchanged throughout this study with the exception of the tracking station coordinate sets used in obtaining orbits from both the laser and the Minitrack data.

The input data and assumptions utilized for this study are outlined in subsections 2.3.1 through 2.3.7.

2.3.1 State Vector

The initial state vector used for this study is as follows:

Epoch: April 12, 1971 00 hrs (Universal Time)

$$X = 1888.9389 \text{ km}$$

$$Y = 5416.6091 \text{ km}$$

$$Z = 4766.2413 \text{ km}$$

$$\dot{X} = 1016.5598 \text{ m/sec}$$

$$\dot{Y} = 5071.3033 \text{ m/sec}$$

$$\dot{Z} = 5330.1954 \text{ m/sec}$$

From this vector an ephemeris was generated to obtain starting vectors for the individual arcs.

Some of the orbital parameters corresponding to the above vector are:

Semi-Major Axis (km)	=	7705.90
Eccentricity	=	0.03225
Inclination (deg)	=	105.80
Perigee ht (km)	=	1082.93
Apogee ht (km)	=	1567.67
Period (min)	=	112.08

2.3.2 Tracking Station Uncertainties

The uncertainties in tracking station coordinates are assumed to be the differences between the two sets of coordinates used in this study. Both sets of tracking station coordinates were obtained from Reference 2. In this report the first set of station coordinates for both laser and Minitrack tracking stations is referred to as the "Unified" set of coordinates. The second set of coordinates is referred to as the "Nonunified" set of coordinates.

Set One: The "Unified" coordinates — This set of coordinates is based on a common center of mass coordinates system as described in Reference 2.

Set Two: The "Nonunified" coordinates — This set of coordinates is based on a variety of geodetic datums as described in Reference 2.

Tables 1 and 2 give the differences in coordinates for laser and Minitrack stations, respectively. The differences represent differences between the "Unified" and "Nonunified" station coordinates (U-N). Note that the largest of these differences are approximately 450 meters (ARELAS) for laser station locations, and approximately 370 meters (SANTIAGO) for Minitrack stations.

Table 1

Differences Between Unified and Nonunified Laser Tracking Station Coordinates

Station Name	$\Delta\phi$ (arc seconds)	$\Delta\lambda$ (arc seconds)	Δh (meters)
GODLAS	0.404	0.405	-53.05
SFLLAS	-4.379	-5.782	67.56
DAKLAS	-4.980	-4.640	148.00
ARELAS	-13.420	-7.010	166.00
OLILAS	-2.810	-1.560	26.00
HOPLAS	0.280	-2.986	-35.10
NATLAS	-13.920	0.230	6.00
GRELAS	-3.850	-3.190	23.00
GMISLS	4.8	-7.9	-41.13

$\Delta\phi$ = unified latitude – nonunified latitude
$\Delta\lambda$ = unified longitude – nonunified longitude
Δh = unified height – nonunified height

Table 2

Differences Between Unified and Nonunified Minitrack Tracking Station Coordinates

Station Name	$\Delta\phi$ (arc seconds)	$\Delta\lambda$ (arc seconds)	Δh (meters)
QUITO	5.650	0.508	-111.60
FTMYR	1.249	0.234	-62.51
SNTAG	8.865	2.311	-249.40
JOBUR	-2.578	-1.721	18.70
WNKFL	-2.710	-6.170	24.63
ULASK	-1.850	-10.378	-8.85
ORORA	4.821	4.155	12.40
MADGA	5.493	-1.171	-17.94

$\Delta\phi$ = Unified Latitude - Non Unified Latitude
$\Delta\lambda$ = Unified Longitude - Non Unified Longitude
Δh = Unified Height - Non Unified Height

The actual coordinates used for each of the stations for both sets are presented in Appendix A.

2.3.3 Observation Data

Laser (range) and Minitrack (direction cosine) data, that were observed for the GEOS-II satellite in the time period from April 23, 1971 through May 21, 1971, were used in this study. The observations were field reduced and used directly from the data base with no additional corrections. The laser data were collected from two GSFC, five Smithsonian Astrophysical Observatory (SAO) and two Centrė National D'Etudes Spatiales (CNES) laser tracking stations. The Minitrack data were collected from eight GSFC Minitrack tracking stations. Appendix A lists station name and location. Appendix B presents the data distribution.

2.3.4 Measurement Uncertainties

For computing weights for the observations, the following uncertainties in measurements were assumed:

Range: ±10 meters

Direction Cosine: $\pm 3 \times 10^{-4}$ (approximately 1 minute of arc)

2.3.5 Geopotential

The earth's gravity field that was used in this study was the SAO 1969 Standard Earth. This earth model is a complete field to order and degree 16, plus selected higher order terms.

A listing of this earth model is presented in Appendix C.

2.3.6 Pertubation Parameters

Effects of the following additional pertubations were taken into account:

(1) Solar gravitation effect with a sun-to-earth mass ratio of

$$\frac{M_{\odot}}{M_{\otimes}} = 332951.25$$

(2) Lunar gravitation effect with a moon to earth mass ratio of

$$\frac{M_{☾}}{M_{\otimes}} = 0.0122999$$

(3) Atmospheric drag effects
Drag coefficient (C_D): 2.300
Satellite cross sectional area = 1.23 meter^2 and
Satellite mass = 211.8 kilograms

(4) Solar radiation pressure effects with
Solar Radiation Pressure = 4.6×10^{-6} Newton/meter^2
Reflectivity = 1.100 and
solar flux variation which are presented in Appendix D.

2.3.7 Numerical Integration

The NONAME Orbit Determination Computer Program uses Cowell's method for solving the equations of motion. A 10th order numerical integrator is used. Throughout this study a fixed time step integration interval of 100 seconds was used.

2.4 Computation Procedure

For the laser (range) data, eleven consecutive four-day orbital arcs were computed, overlapping each other by two days. Data from April 27, 1971 at zero hours U.T.* through May 21, 1971 zero hours U.T. were used. Also, three 14-day long arcs were computed, using laser (range) data, overlapping each other by seven days. Start time of data was April 23, 1971 at zero hours, U.T. and end time of data was May 21, 1971 at zero hours U.T.

For the Minitrack (direction cosine) data, five consecutive four-day orbital arcs were computed overlapping each other by two days, starting on April 27, 1971, and extending through May 9, 1971 at zero hours U.T.

All arcs had estimated starting position and velocity vectors referenced to the midpoint of the orbital arcs. These individual starting vectors were obtained from the initial ephemeris generated for the entire period under study, (i.e., April 23, 1971 to May 21, 1971). Orbits were computed twice, once with the "Unified" station coordinates, and the second time with the "Nonunified" station coordinates. From the converged orbital elements obtained for each arc, a final ephemeris was generated over the data arc span t_L.

Two types of ephemerides comparisons were then made. First, a comparison of resultant ephemerides when "Unified" and "Nonunified" station coordiantes were used. Second, a comparison of the ephemerides in the overlap region when the same station coordinates were used.

*U.T. = Universal Time

3.0 DISCUSSION OF RESULTS

In order to represent the difference in each component of the satellite position vector in the overlap region by one number, the RMS of the differences was formed. That is

ΔR_i = Difference of position vector component in overlap region point i,

N = Total number of ΔR_i in overlap region

$$\text{RMS } (\Delta R) = \left(\frac{\sum_{i=1}^{N} \Delta R_i^2}{N} \right)^{1/2}$$

Similarly, the difference in each component of the satellite position vector between two ephemerides for the same orbital arc, with one arc using the "Unified" and the other arc using the "Nonunified" station locations, is represented by the RMS of the differences over the entire data arc.

Tables 3 and 4 (pages 10, 11) show the resulting RMS values obtained by using the two sets of station coordinates in a direct-arc comparison. Results from 4-day laser-only arcs, 14-day laser-only arcs, and 4-day Minitrack-only arcs are presented. These tables present the direct-arc comparison results and show that the total orbital differences or uncertainties for all the laser-only arcs are of the same order as the uncertainties, or differences, in the laser tracking station coordinates presented earlier in Table 1. The differences for the minitrack-only arcs are of lower order than the differences in the minitrack station coordinates. This indicates that the orbits derived from the laser (range) data are more sensitive to tracking station position than are the orbits derived with Minitrack (direction cosine) data.

Several arcs combining the laser and Minitrack data were also computed for each station coordinate set, and compared. However, because of the small amount of Minitrack data compared to the laser data, the results were not much different than those obtained from the laser alone.

Figures 3 and 4 (pages 21, 23) present sample trajectory differences from the entire arcs for the April 27, 1971 through May 1, 1971 time period for laser and Minitrack data, respectively.

Table 3

RMS of Position Vector Components Differences from Ephemeris Comparisons for Definitive Orbits Computed Using Unified and Nonunified Laser Station Coordinates

	Period		RMS of Position Vector Component Differences (meters)			
	From YYMMDD	To YYMMDD	Radial	Cross Track	Along Track	Total
4 Day Arcs	71 04 27	71 05 01	85.03	450.10	212.39	504.91
	71 04 29	71 05 03	147.04	184.72	344.80	417.89
	71 05 01	71 05 05	165.88	146.34	383.13	442.41
	71 05 03	71 05 07	119.51	256.08	253.27	379.48
	71 05 05	71 05 09	95.63	64.37	227.86	255.36
	71 05 07	71 05 11	162.57	88.65	354.14	399.63
	71 05 09	71 05 13	129.84	201.10	309.14	390.99
	71 05 11	71 05 15	96.68	98.43	207.00	248.76
	71 05 13	71 05 17	22.19	78.68	505.36	511.93
	71 05 15	71 05 19	124.08	327.31	301.47	461.97
	71 05 17	71 05 21	96.00	175.41	245.72	316.80
14 Day Arcs	71 04 23	71 05 07	71.29	184.91	145.11	245.62
	71 04 30	71 05 14	129.13	59.69	302.78	334.54
	71 05 07	71 05 21	106.85	127.99	223.31	278.69

Table 4

RMS of Position Vector Components Differences from Ephemeris Comparisons for Definitive Orbits Computed Using Unified and Nonunified Minitrack Station Coordinates

	Period		RMS of Position Vector Component Differences (meters)			
	From YYMMDD	To YYMMDD	Radial	Cross Track	Along Track	Total
4 Day Arcs	71 04 27	71 05 01	11.54	45.01	72.81	86.38
	71 04 29	71 05 03	16.28	15.99	45.28	50.71
	71 05 01	71 05 05	11.48	36.62	78.10	87.02
	71 05 03	71 05 07	37.64	34.36	94.92	107.74
	71 05 05	71 05 09	22.60	128.92	134.73	187.83

Tables 5 and 6 (pages 12, 13) show the orbital uncertainty estimates in the overlap region for the laser data and Minitrack data respectively, when the "Unified" station coordinates were used.

Tables 7 and 8 (pages 14, 15) show the orbital uncertainty estimates for the laser data and Minitrack data respectively, when the "Nonunified" station coordinates were used.

As can be seen from Tables 5 through 8, the "Unified" laser station coordinates improved orbital uncertainty estimates by an order of magnitude over the "Nonunified" station coordinates. Some improvement can be noted when the "Unified" Minitrack station coordinates are used. The Minitrack orbits exhibit a lesser sensitivity to station coordinates probably because of the relatively lower number of Minitrack observational data compared to laser data and also due to the fact that Minitrack observations are less precise (1×10^{-4} radians or $\approx$100 meters) than laser observations ($\pm$1 meter). The OUE results for the "Unified" coordinates range from 45 meters to 145 meters, whereas for the "Nonunified" coordinates the OUE results range from 180 meters to 625 meters. Similar results were obtained for the 14-day arcs.

Figures 5 through 8 (pages 25-31) represent the OUE results for the entire overlap region between two consecutive arcs for "Unified" laser stations, "Unified" Minitrack stations, "Nonunified" laser stations, and "Nonunified" Minitrack stations, respectively. The overlap region represented is from April 29, 1971 through May 1, 1971 in all of these figures.

Table 5

RMS of Position Vector Components Differences from Ephemeris Comparisons in Overlap Regions Using Unified Laser Station Coordinates

	Overlap Interval		RMS of Position Vector Component Differences (meters)			
	From YYMMDD	To YYMMDD	Radial	Cross Track	Along Track	Total
4 Day Arcs	71 04 29	71 05 01	4.04	22.67	15.36	27.68
	71 05 01	71 05 03	4.93	22.64	18.41	29.60
	71 05 03	71 05 05	12.95	39.39	34.97	54.24
	71 05 05	71 05 07	10.49	36.78	25.91	46.20
	71 05 07	71 05 09	8.40	22.79	41.60	48.17
	71 05 09	71 05 11	7.18	48.67	46.20	67.49
	71 05 11	71 05 13	19.24	40.22	60.55	75.19
	71 05 13	71 05 15	35.41	30.49	136.55	144.32
	71 05 15	71 05 17	22.79	22.19	68.57	75.59
	71 05 17	71 05 19	13.62	19.79	43.77	49.93
14 Day Arcs	71 04 30	71 05 07	5.35	10.74	93.65	94.42
	71 05 07	71 05 14	13.66	22.26	64.73	69.80

Table 6

RMS of Position Vector Components Differences from Ephemeris Comparisons in Overlap Regions Using Unified Minitrack Station Coordinates

	Overlap Interval		RMS of Position Vector Component Differences (meters)			
	From YYMMDD	To YYMMDD	Radial	Cross Track	Along Track	Total
4 Day Arcs	71 04 29	71 05 01	3.80	54.18	60.38	81.21
	71 05 01	71 05 03	11.31	30.04	43.06	53.71
	71 05 03	71 05 05	8.05	55.39	43.24	70.73
	71 05 05	71 05 07	98.39	146.99	204.59	270.45

Table 7

RMS of Position Vector Components Differences from Ephemeris Comparisons in Overlap Regions Using Nonunified Laser Station Coordinates

	Overlap Interval		RMS of Position Vector Component Differences (meters)			
	From YYMMDD	To YYMMDD	Radial	Cross Track	Along Track	Total
4 Day Arcs	71 04 29	71 05 01	63.94	556.38	166.14	584.16
	71 05 01	71 05 03	55.84	173.42	130.69	224.22
	71 05 03	71 05 05	74.46	183.69	212.62	290.68
	71 05 05	71 05 07	51.21	249.34	135.28	288.26
	71 05 07	71 05 09	63.73	101.68	135.79	181.22
	71 05 09	71 05 11	50.39	176.69	137.97	229.77
	71 05 11	71 05 13	58.02	164.39	161.72	237.79
	71 05 13	71 05 15	46.67	103.41	436.28	450.79
	71 05 15	71 05 17	101.90	262.99	557.21	624.53
	71 05 17	71 05 19	39.48	203.25	99.79	229.84
14 Day Arcs	71 04 30	71 05 07	58.50	190.24	204.55	285.40
	71 05 07	71 05 14	19.66	110.23	63.26	128.60

Table 8

RMS of Position Vector Components Differences from Ephemeris Comparisons in Overlap Regions Using Nonunified Minitrack Station Coordinates

	Overlap Interval		RMS of Position Vector Component Differences (meters)			
	From YYMMDD	To YYMMDD	Radial	Cross Track	Along Track	Total
4 Day Arc	71 04 29	71 05 01	7.94	97.20	92.19	134.20
	71 05 01	71 05 03	9.47	77.92	38.57	87.46
	71 05 03	71 05 05	39.38	35.85	79.70	95.85
	71 05 05	71 05 07	52.54	13.80	123.17	134.62

From individual arc statistics presented in Tables 9 through 12 (pages 16-19), the same trend is noted. In this case, the statistic of merit is the standard deviation of fit which ranged from a low of 14 meters to a high of 30 meters. For the "Nonunified" laser station, the range of standard deviation of fit is from a low of 80 meters to a high of 138 meters. Minitrack results again show little improvement.

Table 9

Definitive Orbit Results for Arcs Using Unified Laser Station Coordinates

	Time-Span		Number of Observations per Orbital Arc by Station							Total No. of Obser-vations Used	Standard Deviation of Fit (meters)
	From YYMMDD	To YYMMDD	GODLAS	ARELAS	OLILAS	NATLAS	GMISLS	HOPLAS	SFLLAS		
4 Day Arcs	71 04 27	71 05 01	32	17	10	24	47			130	19.86
	71 04 29	71 05 03	20	43	21	19		15	5	123	21.65
	71 05 01	71 05 05	2	61	11			15	5	94	16.10
	71 05 03	71 05 07		28	8	1	9	22		68	14.56
	71 05 05	71 05 09		25	19	1	22	29		96	14.37
	71 05 07	71 05 11		45	18	15	13	8		99	20.51
	71 05 09	71 05 13	34	20	21	49	36	5		165	27.38
	71 05 11	71 05 15	34		25	34	50	4		147	24.22
	71 05 13	71 05 17		17	20		14	13		64	23.28
	71 05 15	71 05 19	9	11	53	1		13		118	19.69
	71 05 17	71 05 21	18	79	81	6	19			203	26.45
14 Day Arcs	71 04 23	71 05 07	58	85	38	25	71	37	5	319	23.07
	71 04 30	71 05 14	52	116	51	50	58	49	5	381	30.06
	71 05 07	71 05 21	52	141	133	55	82	25		488	30.46

Table 10

Definitive Orbit Results for Arcs Using Unified Minitrack Station Coordinates

Time-Span		Number of Observations per Orbital Arc by Station								Total No. of Obser-vations Used	Standard Deviation of Fit (milli-radians)
From YYMMDD	To YYMMDD	FTMYR	QUITO	SNTAG	JOBUR	WNKFL	ULASK	ORORA	MADGA		
71 04 27	71 05 01	18	2	2	4	6	6	1	3	42	0.183
71 04 29	71 05 03	20	2	2	4	6	4	1	3	42	0.168
71 05 01	71 05 05	14	2	2	4	8	4	2	2	38	0.135
71 05 03	71 05 07	10	2	6	4	4	2	8	2	38	0.113
71 05 05	71 05 09	6	2	4	4	4	4	8	7	39	0.150

Table 11

Definitive Orbit Results for Arcs Using Nonunified Laser Station Coordinates

	Time-Span		Number of Observations per Orbital Arc by Station							Total No. of Obser-vations Used	Standard Deviation of Fit (meters)
	From YYMMDD	To YYMMDD	GODLAS	ARELAS	OLILAS	NATLAS	GMISLS	HOPLAS	SFLLAS		
4 Day Arcs	71 04 27	71 05 01	32	17	10	26	47			132	92.41
	71 04 29	71 05 03	20	43	21	20		15	5	124	83.90
	71 05 01	71 05 05	2	61	11			15	5	94	109.07
	71 05 03	71 05 07		28	8	1	9	23		69	108.91
	71 05 05	71 05 09		25	20	1	22	29		97	97.45
	71 05 07	71 05 11		45	19	15	13	10		102	100.69
	71 05 09	71 05 13	34	20	21	49	36	7		169	99.99
	71 05 11	71 05 15	34	1	26	34	50	4		149	80.63
	71 05 13	71 05 17		20	21	2	14	13		70	137.95
	71 05 15	71 05 19	10	41	53	1	1	13		119	83.03
	71 05 17	71 05 21	19	79	81	7	19			205	98.17
14 Day Arcs	71 04 23	71 05 07	58	86	38	27	71	37	5	322	121.79
	71 04 30	71 05 14	52	117	52	50	58	52	5	386	115.08
	71 05 07	71 05 21	53	143	136	57	82	26		497	106.00

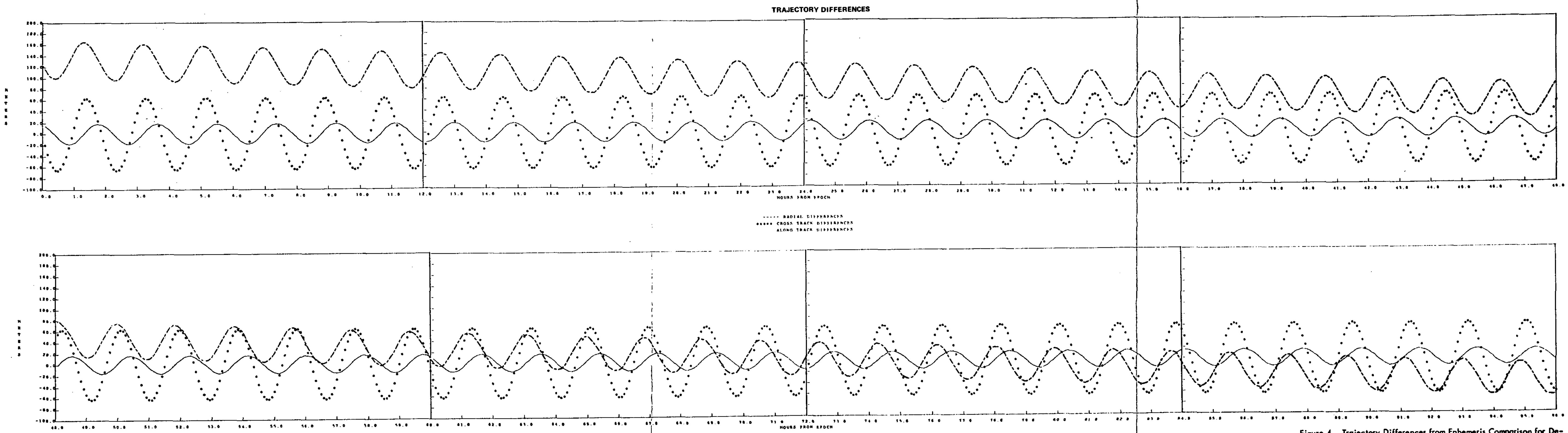
Table 12

Definitive Orbit Results for Arcs Using Nonunified Minitrack Station Coordinates

Time-Span		Number of Observations Used per Orbital Arc by Station								Total No. of Obser-vations Used	Standard Deviation of Fit (milli-radians)
From YYMMDD	To YYMMDD	FTMYR	QUITO	SNTAG	JOBUR	WNKFL	ULASK	ORORA	MADGA		
71 04 27	71 05 01	18	2	2	4	6	6	1	3	42	0.179
71 04 29	71 05 03	20	2	2	4	6	4	1	3	42	0.180
71 05 01	71 05 05	14	2	2	4	8	4	2	2	38	0.151
71 05 03	71 05 07	10	2	6	4	4	2	8	2	38	0.140
71 05 05	71 05 09	6	2	4	4	4	4	8	7	39	0.156

FOLDOUT FRAME 1

FOLDOUT FRAME 2



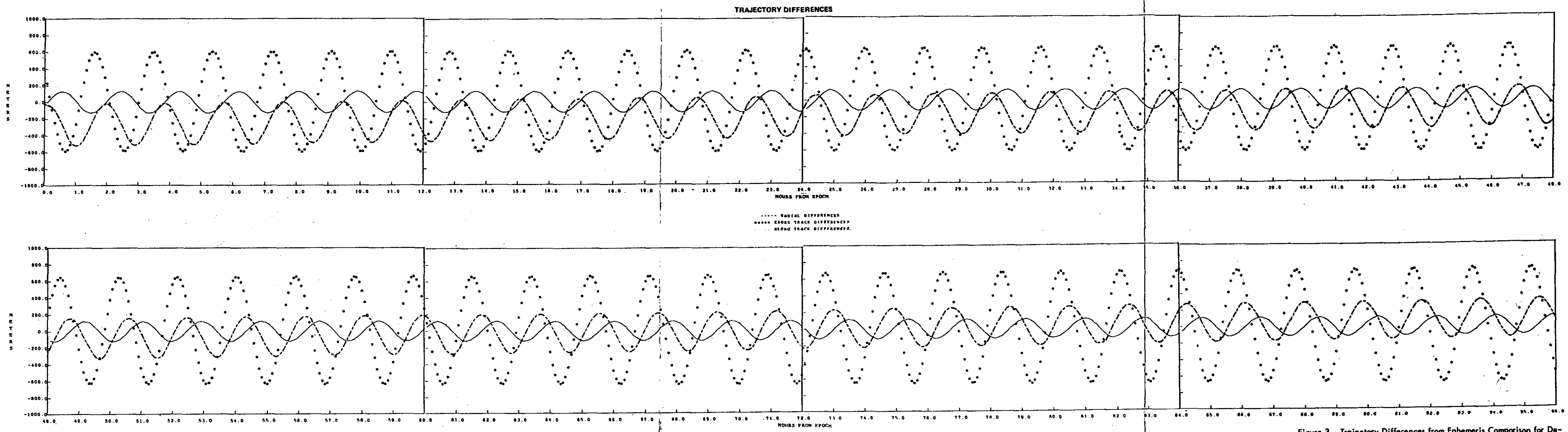
RMS of Position Differences (Meters)

Radial	Cross Track	Along Track	Total
11.54	45.01	72.81	86.38

Figure 4. Trajectory Differences from Ephemeris Comparison for Definitive Orbits Computed Using Unified and Nonunified Minitrack Tracking Stations and minitrack direction cosine data. Period of Comparison April 27, 1971 Zero Hours U.T. to May 1, 1971 Zero Hours U.T.

FOLDOUT FRAME 1

FOLDOUT FRAME 2



RMS of Position Differences (Meters)

Radial	Cross Track	Along Track	Total
85.03	450.10	212.39	504.91

Figure 3. Trajectory Differences from Ephemeris Comparison for Definitive Orbits Computed Using Unified and Nonunified Laser Tracking Stations and Laser Range data. Period of Comparison April 27, 1971 Zero Hours U.T. to May 1, 1971 Zero Hours U.T.

22

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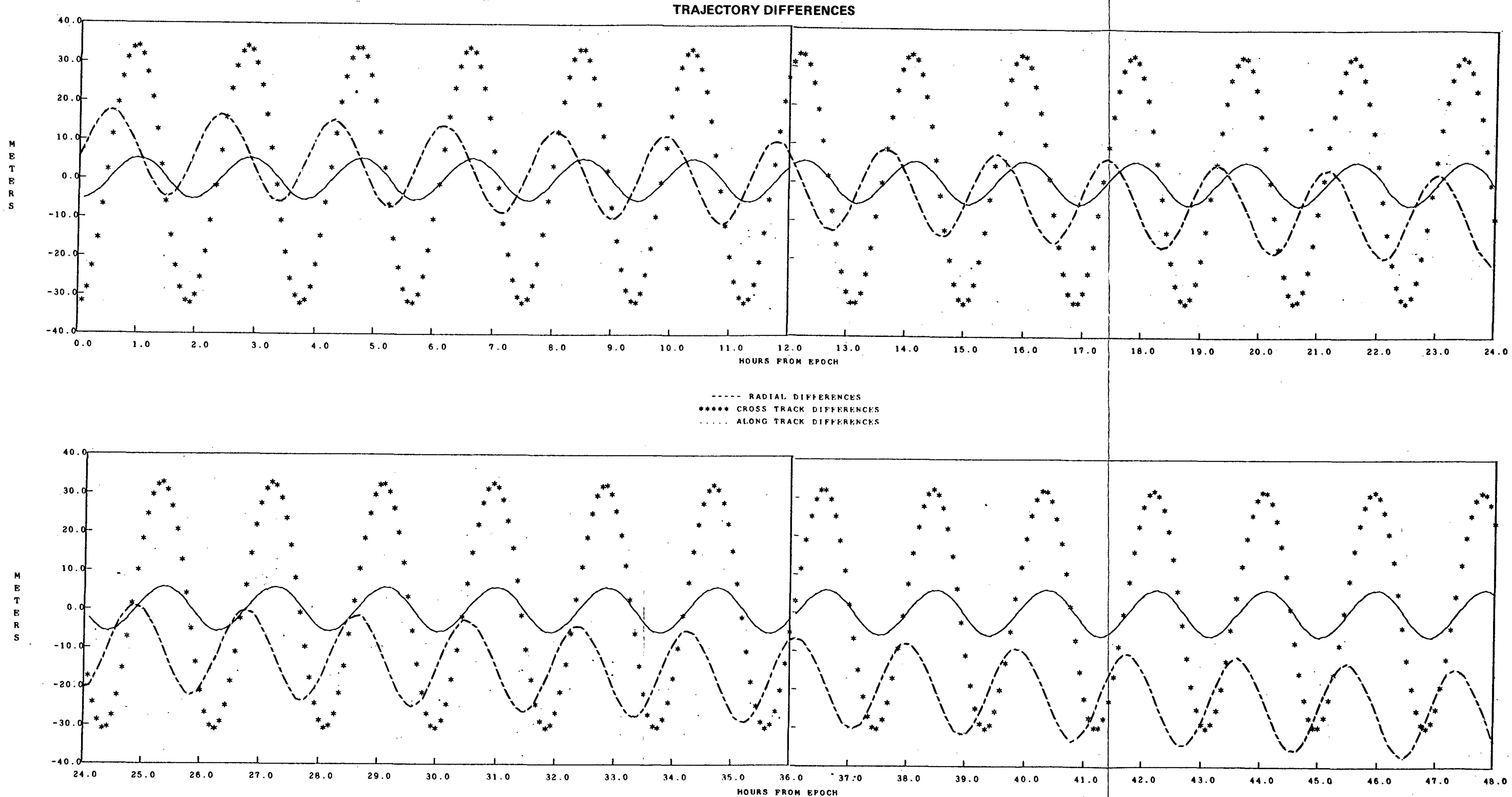

24

RMS of Position Differences (Meters)

Radial	Cross Track	Along Track	Total
4.04	22.67	15.36	27.68

Figure 5. Trajectory Differences from Ephemeris Comparison in Overlap Region Using Unified Laser Station Coordinates. Overlap Span April 29, 1971 Zero Hours U.T. to May 1, 1971 Zero Hours U.T.

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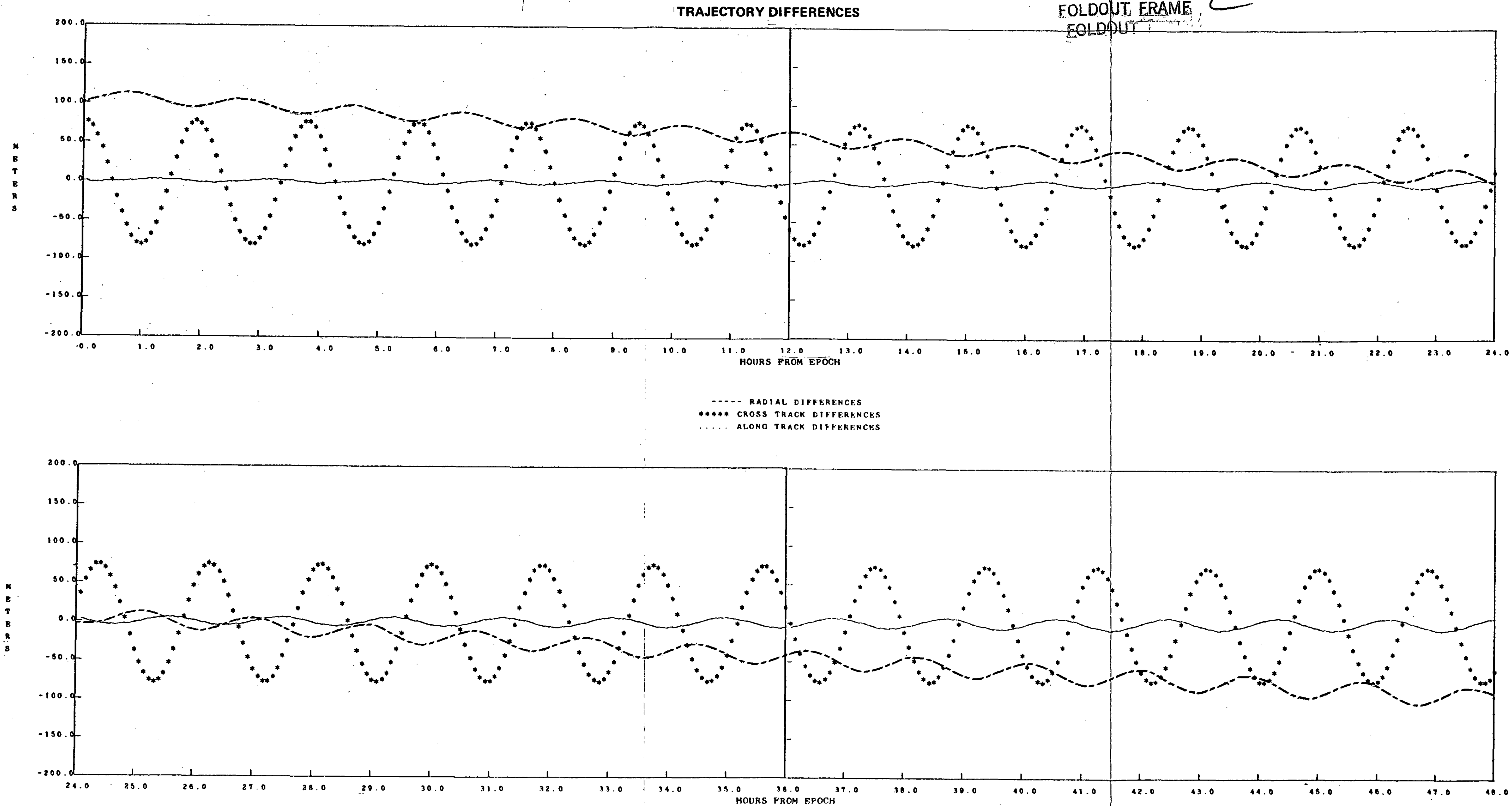

Figure 6. Trajectory Differences from Ephemeris Comparison in Overlap Region Using Unified Minitrack Station Coordinates. Overlap Span April 29, 1971 Zero Hours U.T. to May 1, 1971 Zero Hours U.T.

RMS of Position Differences (Meters)

Radial	Cross Track	Along Track	Total
3.80	54.18	60.38	81.21

26

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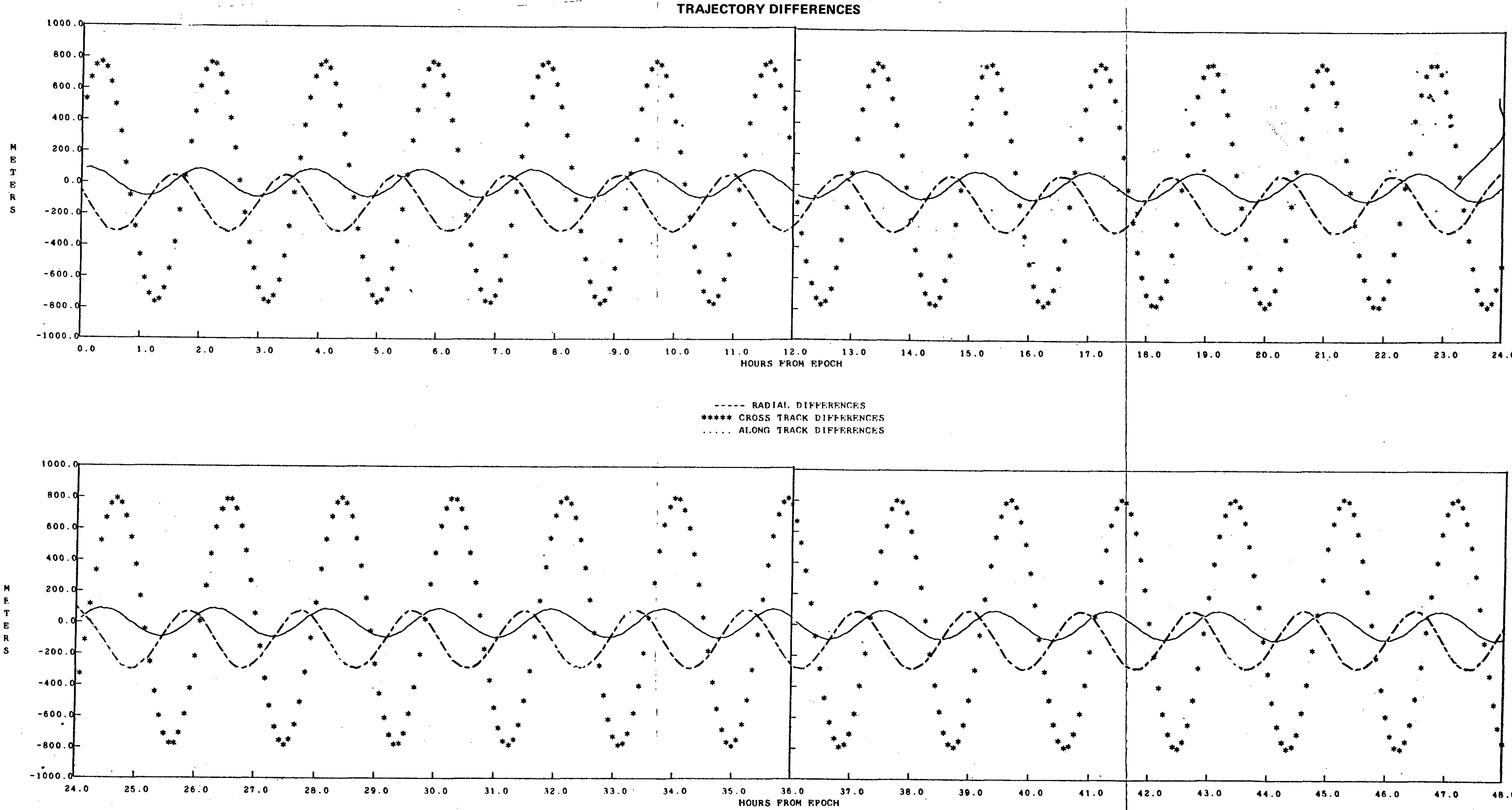

Figure 7. Trajectory Differences from Ephemeris Comparison Overlap Region Using Nonunified Laser Station Coordinates. Overlap Span April 29, 1971 Zero Hours U.T. to May 1, 1971 Zero Hours U.T.

RMS of Position Differences (Meters)

Radial	Cross Track	Along Track	Total
63.94	556.38	166.14	584.16

28

FOLDOUT FRAME 1

FOLDOUT FRAME 2

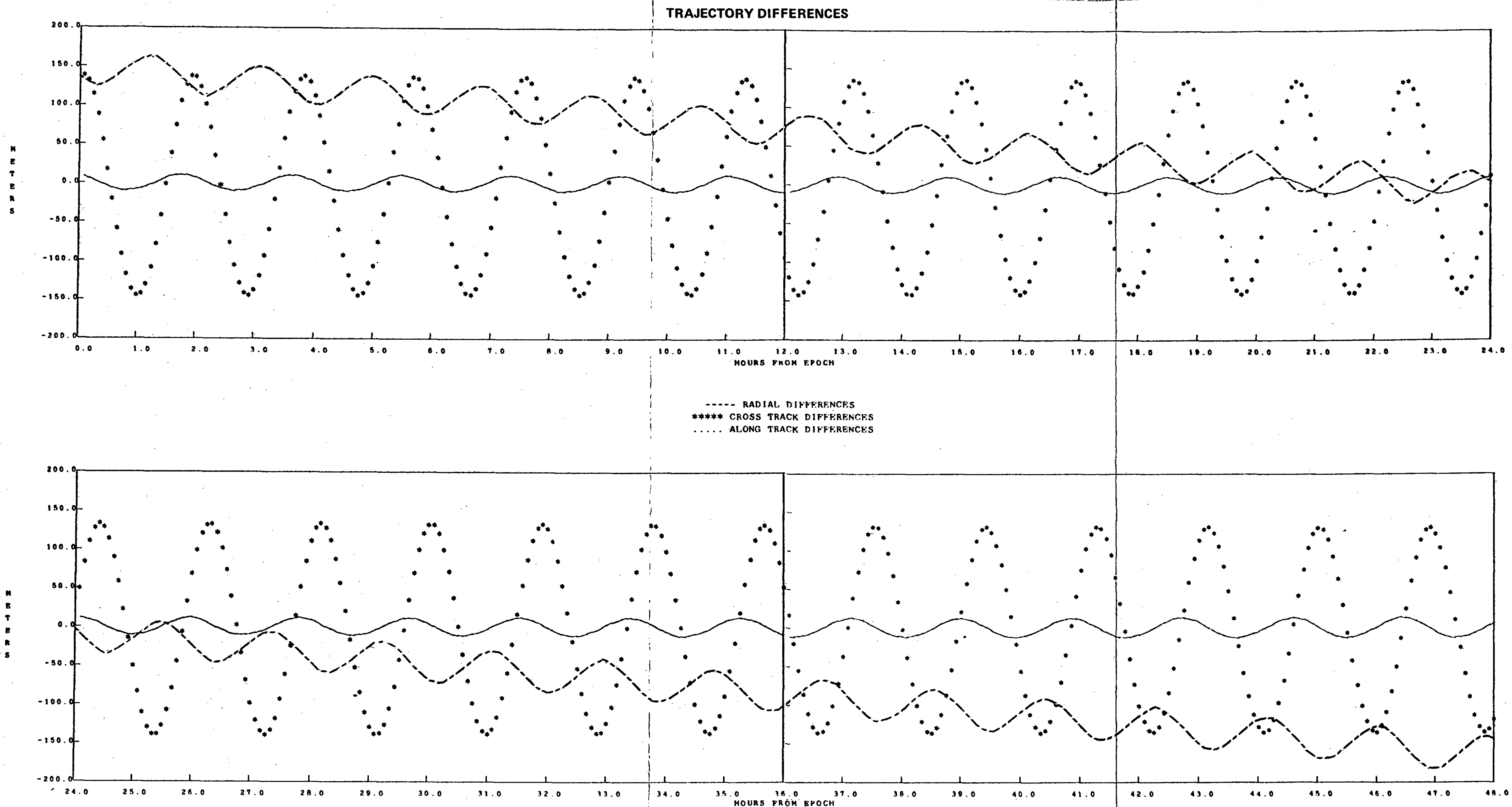

Figure 8. Trajectory Differences from Ephemeris Comparison in Overlap Region Using Nonunified Minitrack Station Coordinates. Overlap Span April 29, 1971 Zero Hours U.T. to May 1, 1971 Zero Hours U.T.

RMS of Position Differences (Meters)

Radial	Cross Track	Along Track	Total
7.94	97.20	92.19	134.20

30

4.0 CONCLUSIONS

The significant reduction in the RMS of the observation residuals coupled with the lower orbital uncertainty estimate (OUE) values obtained in the overlaps when the "Unified" sets of station coordinates were used for both the laser and Minitrack data, show that use of the "Unified" sets of station positions contributed to improved estimates of the GEOS-II orbit.

RMS residuals for orbits determined using the "Unified" laser station coordinates were reduced by as much as a factor of seven relative to determinations using the "Nonunified" laser station coordinates. Orbits determined from Minitrack data exhibited much smaller residual reduction than those for laser data although the differences between the "Unified" and "Nonunified" Minitrack station coordinates were of the same order as the laser station differences. This variation in the degree of improvement between laser orbits and minitrack orbits is understandable in light of the fact that there were five times as many laser measurements as there were Minitrack measurements and the resultant Minitrack measurements had inherent noise levels which were higher relative to the changes in the station locations used in this study. Consequently, the Minitrack orbits were less sensitive to the station coordinate changes than the laser orbits.

Thus, in summary, the "Unified" station location coordinates significantly improved orbital accuracy obtained with laser (range) data observations and to a lesser degree also improved orbits obtained with Minitrack (direction cosine) data.

5.0 ACKNOWLEDGEMENT

The authors wish to express their appreciation to Dr. F. O. Vonbun, Chief of the Trajectory Analysis and Geodynamics Division, for suggesting this study.

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APPENDIX A

Tables A-1 through A-4 present the station coordinates used in this study.

Table A-1 - The Unified Laser Coordinates

Table A-2 - The Unified Minitrack Coordinates

Table A-3 - The Nonunified Laser Coordinates

Table A-4 - The Nonunified Minitrack Coordinates

Figure A-1 - World Map Indicating the Station Locations

Table A-1

Unified Laser Station Coordinates

Name	Location	Latitude			East Longitude			Height
		(deg)	(min)	(sec)	(deg)	(min)	(sec)	(meters)
GODLAS	Greenbelt, Maryland	39	01	14.08	283	10	18.44	3.0
OLILAS	Olifantsfontein, Rep. of South Africa	-25	57	36.66	28	14	52.35	1570.0
ARELAS	Arequipa, Peru	-16	27	57.21	288	30	24.53	2488.0
NATLAS	Natal, Brazil	-5	55	41.39	324	50	07.21	44.0
GRELAS	Dionysos, Greece	38	04	42.31	23	55	56.80	490.0
HOPLAS	Mt. Hopkins, Arizona	31	41	03.15	249	07	18.36	2339.0
SFLLAS	San Fernando, Spain	36	27	45.73	353	47	35.49	56.0
DAKLAS	Dakar, Senegal	14	44	32.42	342	30	24.86	171.0
GMISLS	Guam	13	18	33.37	144	44	13.34	127.0

Table A-2

Unified Minitrack Station Coordinates

Name	Location	Latitude			East Longitude			Height
		(deg)	(min)	(sec)	(deg)	(min)	(sec)	(meters)
QUITO	Quito, Ecuador	-00	37	22.35	281	25	15.32	3557.0
FTMYR	Fort Myers, Florida	26	32	53.140	278	08	04.16	-42.0
ULASK	Fairbanks, Alaska	64	58	36.75	212	28	30.52	283.0
WNKFL	Winkfield, England	51	26	46.40	359	18	07.93	90.0
JOBUR	Johannesburg, Rep. of South Africa	-25	53	01.44	27	42	26.21	1541.0
SNTAG	Santiago, Chile	-33	08	58.79	289	19	53.66	714.0
ORORA	Orroral, Australia	-35	37	32.68	148	57	14.85	950.0
MADGA	Tananarive, Madagascar	-19	00	32.59	47	17	59.29	1360.0

Table A-3

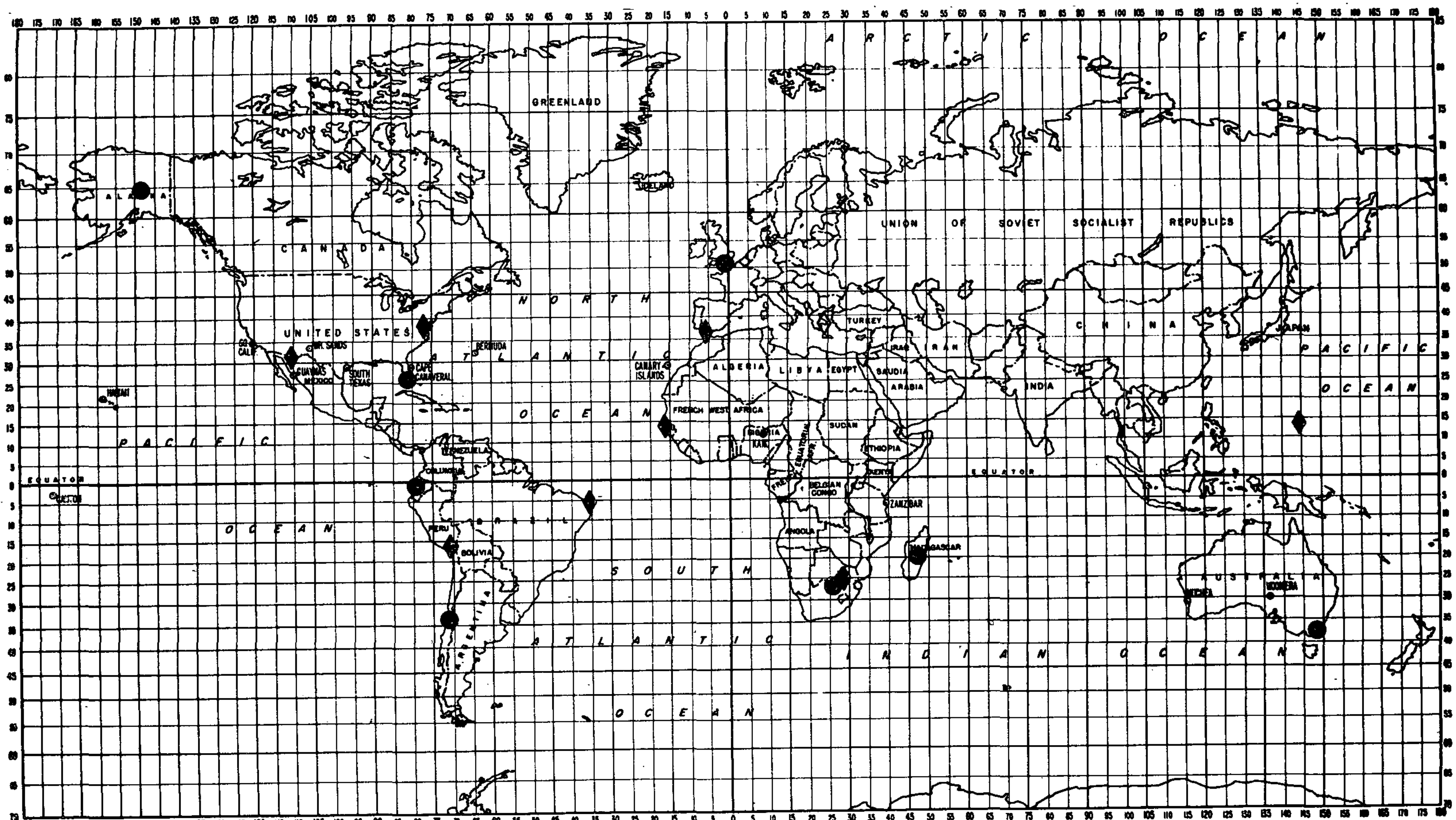
Nonunified Laser Station Coordinates

Name	Location	Latitude			East Longitude			Height
		(deg)	(min)	(sec)	(deg)	(min)	(sec)	(meters)
GODLAS	Greenbelt, Maryland	39	01	13.676	283	10	18.035	56.05
OLILAS	Olifantsfontein, Rep. of South Africa	-25	57	33.85	28	14	53.91	1544.0
ARELAS	Arequipa, Peru	-16	27	43.79	288	30	31.54	2322.0
NATLAS	Natal, Brazil	-5	55	27.47	324	50	06.98	38.0
GRELAS	Dionysos, Greece	38	04	46.16	23	55	59.99	467.0
HOPLAS	Mt. Hopkins, Arizona	31	41	02.870	249	07	21.346	2374.1
SFLLAS	San Fernando, Spain	36	27	50.109	353	47	41.272	-11.56
DAKLAS	Dakar, Senegal	14	44	37.40	342	30	29.50	23.0
GMISLS	Guam	13	18	33.37	144	44	13.34	127.0

Table A-4

Nonunified Minitrack Station Coordinates

Name	Location	Latitude			East Longitude			Height
		(deg)	(min)	(sec)	(deg)	(min)	(sec)	(meters)
QUITO	Quito, Ecuador	-00	37	28.00	281	25	14.812	3668.6
FTMYR	Fort Myers, Florida	26	32	51.891	278	08	03.926	20.51
ULASK	Fairbanks, Alasks	64	58	38.600	212	28	40.898	291.85
WNKFL	Winkfield, England	51	26	49.110	359	18	14.10	65.37
JOBUR	Johannesburg, Rep. of South Africa	-25	52	58.862	27	42	27.931	1522.3
SNTAG	Santiago, Chile	-33	09	07.655	289	19	51.349	963.4
ORORA	Orroral, Australia	-35	37	37.501	148	57	10.705	937.6
MADGA	Tananarive, Madagascar	-19	00	27.097	47	18	00.461	1377.94



MINITRACK STATIONS

LASER STATIONS

Figure A-1. World Map Indicating the Station Locations

APPENDIX B

The data distribution for both the laser (range) and Minitrack (direction cosine) types, is presented in Tables B-1 and B-2 respectively. The distribution is in terms of observations within a 48 hour interval. For the minitrack data type an observation count is a direction cosine pair.

The first interval starts April 27, 1971 zero hours U.T. and ends on April 29, 1971 zero hours U.T. The second interval starts on April 29, 1971 zero hours U.T., and ends 48 hours later, and so forth. The last interval begins on May 19, 1971 zero hours U.T. and ends on May 21, 1971 zero hours U.T.

Table B-1

Laser Range Data Distribution

Station / Interval* No.	1	2	3	4	5	6	7	8	9	10	11	12
GODLASS	14	18	2	0	0	0	0	60	0	0	10	9
ARELASS	8	12	37	29	3	26	23	0	7	19	25	55
GMISLSS	47	0	0	0	9	13	0	36	14	0	1	18
DAKLASS	3	5	5	0	0	0	0	0	0	0	0	0
NATLASS	6	22	0	0	1	0	15	34	4	1	2	9
OLILASS	20	10	11	0	8	12	8	14	12	10	45	39
HOPLASS	0	0	15	0	25	7	27	5	0	13	0	0
GRELASS	1	0	0	0	0	0	0	8	0	0	1	0
SFLLASS	0	0	5	0	0	0	0	0	0	0	0	0
Totals	99	67	75	29	46	58	73	157	37	43	84	130

*Each interval consists of 48 hours of data (two days) starting on April 27 through Mary 21, 1971 exclusive.

Table B-2

Minitrack* Data Distribution

Station / Interval** No.	1	2	3	4	5	6	7	8	9	10	11	12
ULASK	3	0	2	1	1	1	1	1	1	0	1	0
FTMYR	3	6	4	3	2	1	4	2	2	2	3	3
SNTAG	0	1	1	0	2	0	0	0	1	0	0	0
QUITO	0	1	0	1	0	1	0	0	1	0	0	0
MADGA	1	1	1	0	1	3	2	0	0	0	0	2
WNKFL	2	1	2	2	0	2	1	2	2	1	2	3
ORORA	0	1	1	0	3	1	0	1	0	0	1	0
JOBURG	1	1	1	1	2	1	1	1	3	1	0	2
Totals	10	12	12	8	11	10	9	7	10	4	7	10

*Direction cosine pairs.
**An interval consists of 48 hours (two days) starting on April 27, 1971 through May 21 exclusive.

APPENDIX C

SAO 1969 STANDARD EARTH

SAO 1969 STANDARD EARTH

ZONALS

INDEX N	M	VALUE	INDEX N	M	VALUE	INDEX N	M	VALUE	INDEX N	M	VALUE	INDEX N	M	VALUE
2	0	-1.08263E-03	3	0	2.53800E-06	4	0	1.59300E-06	5	0	2.30000E-07	6	0	-5.02000E-07
7	0	3.62000E-07	8	0	1.18000E-07	9	0	1.00000E-07	10	0	3.54000E-07	11	0	-2.02000E-07
12	0	-4.20000E-08	13	0	1.23000E-07	14	0	-7.30000E-08	15	0	1.74000E-07	16	0	-1.87000E-07
17	0	-8.49999E-08	18	0	2.31000E-07	19	0	2.16000E-07	20	0	5.00000E-09	21	0	-1.44000E-07

SECTORIALS AND TESSERALS

INDEX N	M	VALUE C	S	INDEX N	M	VALUE C	S	INDEX N	M	VALUE C	S
2	2	1.55752E-06	-8.80522E-07	3	1	2.12763E-06	2.80994E-07	3	2	3.04690E-07	-2.15784E-07
3	3	9.56999E-08	1.99460E-07	4	1	-5.02698E-07	-4.62625E-07	4	2	7.38439E-08	1.57940E-07
4	3	5.91297E-08	-9.24330E-09	4	4	-1.58380E-09	7.15859E-09	5	1	-4.60853E-08	-8.38607E-08
5	2	9.91820E-08	-5.67829E-08	5	3	-1.42322E-08	-2.86286E-09	5	4	-2.07839E-09	6.66339E-10
5	5	3.10069E-10	-1.47513E-09	6	1	-7.78801E-08	2.962[illegible]E-08	6	2	6.82041E-09	-4.37589E-08
6	3	5.77915E-10	9.25271E-10	6	4	-1.52714E-12	-1.52888E-09	6	5	-1.70638E-10	-4.21805E-10
6	6	2.06637E-11	-1.74156E-11	7	1	1.78701E-07	8.45617E-08	7	2	2.81934E-08	1.55828E-08
7	3	2.85732E-09	-2.30286E-09	7	4	-4.18909E-10	-2.41870E-10	7	5	-3.07997E-13	3.48475E-11
7	6	-1.79603E-11	7.08604E-12	7	7	2.95250E-12	-1.25606E-12	8	1	2.14773E-08	1.76579E-08
8	2	3.95567E-09	6.91077E-09	8	3	-5.80760E-10	1.82830E-10	8	4	-2.00713E-10	9.82344E-11
8	5	-1.02686E-11	1.11560E-11	8	6	-1.50544E-12	7.24190E-12	8	7	1.75356E-13	4.54672E-13
8	8	-9.86207E-14	8.61829E-14	9	1	8.98199E-08	-1.04616E-08	9	2	4.62298E-10	-5.66143E-09
9	3	-7.29038E-10	-8.93093E-10	9	4	4.88842E-11	9.56975E-11	9	5	-6.28361E-13	3.43162E-13
9	6	3.19361E-13	2.90856E-12	9	7	-9.61519E-14	-2.42047E-13	9	8	7.63504E-14	1.87090E-14
9	9	-6.35510E-15	7.11287E-15	10	1	6.95215E-08	-6.28233E-08	10	2	-1.85660E-09	-6.21344E-09
10	3	-1.36117E-10	-8.24246E-10	10	4	-2.83791E-11	-2.54714E-11	10	5	-4.96580E-12	-8.86468E-12
10	6	-2.25484E-13	-1.39881E-12	10	7	4.62616E-14	2.69375E-14	10	8	8.47126E-15	-9.12977E-15
10	9	-1.27399E-16	1.16130E-15	10	10	5.14254E-16	-1.07550E-16	11	1	2.59153E-09	1.75628E-08
11	2	2.53180E-09	-4.78299E-09	11	3	-2.91726E-10	-6.04650E-10	11	4	-1.27131E-11	2.28707E-11
11	5	1.29397E-12	5.25778E-12	11	6	1.67796E-13	2.71842E-14	11	7	1.89879E-14	-5.75625E-14
11	8	3.07451E-15	-8.09426E-16	11	9	7.22552E-15	-6.11562E-17	11	10	-1.11359E-16	-1.79336E-17
11	11	2.38410E-17	-8.23118E-18	12	1	-2.60169E-08	-1.75503E-08	12	2	1.25370E-09	3.46654E-09
12	3	2.17483E-10	2.04066E-10	12	4	-1.35491E-11	-6.91034E-12	12	5	6.22182E-13	1.13489E-12
12	6	-5.55974E-14	-1.58330E-13	12	7	3.22185E-15	2.21610E-16	12	8	-1.28488E-16	7.49597E-16
12	9	-7.81045E-17	1.03853E-16	12	10	-5.50493E-18	1.44311E-18	12	11	-1.97555E-18	-2.12001E-18
12	12	-1.74217E-19	-5.18611E-19	13	1	-3.05263E-08	1.43192E-08	13	2	-1.92671E-09	7.05098E-10
13	3	7.29369E-11	-8.85334E-11	13	4	-4.68986E-12	1.33859E-11	13	5	1.78209E-12	-8.80746E-13
13	6	-1.24773E-13	8.94201E-14	13	7	-6.60104E-15	-4.11635E-16	13	8	-5.70290E-16	-2.27841E-16
13	9	-2.75137E-17	1.15615E-16	13	10	9.59366E-18	-1.17861E-18	13	11	-4.45266E-19	7.72352E-19
13	12	-2.46832E-21	1.53357E-19	13	13	-2.57198E-20	2.73134E-20	14	1	-1.21347E-08	2.61003E-08

SECTORIALS AND TESSERALS
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INDEX N	INDEX M	VALUE C	VALUE S	INDEX N	INDEX M	VALUE C	VALUE S	INDEX N	INDEX M	VALUE C	VALUE S
14	2	1.17044E-09	-1.65031E-09	14	3	4.85814E-11	3.04087E-12	14	4	1.41454E-12	-6.80407E-12
14	5	-3.41444E-13	-3.07050E-13	14	6	1.87652E-14	-5.75712E-14	14	7	8.36565E-16	6.36383E-16
14	8	-1.84524E-16	-2.70827E-16	14	9	2.57042E-17	4.79149E-17	14	10	2.64507E-18	-2.04470E-18
14	11	1.31834E-19	-3.86682E-19	14	12	5.59374E-21	-3.07383E-20	14	13	3.76257E-21	3.31730E-21
14	14	-7.18342E-22	-1.77096E-22	15	1	-1.82828E-09	2.04028E-08	15	2	-1.47706E-09	-5.28980E-10
15	3	1.78795E-11	-1.23233E-11	15	4	1.98491E-12	9.50577E-12	15	5	3.04688E-13	1.75600E-14
15	6	4.64651E-14	-7.87824E-15	15	7	5.59127E-15	2.01325E-15	15	8	-3.39521E-15	-1.24152E-16
15	9	5.91825E-18	7.14353E-18	15	10	-6.52211E-19	1.17661E-20	15	11	-6.25906E-20	1.80659E-19
15	12	1.92518E-21	1.27028E-21	15	13	-7.53195E-22	8.11700E-23	15	14	3.22877E-23	-7.09307E-23
15	15	7.01751E-25	-7.15626E-24	16	1	-1.17183E-08	3.75408E-08	16	2	6.39345E-10	9.19401E-10
16	3	-8.70479E-11	5.99398E-11	16	4	-1.32129E-12	4.90181E-12	16	5	-3.17402E-13	2.31440E-13
16	6	-2.69757E-14	-1.97608E-14	16	7	3.22361E-15	2.65565E-15	16	8	-1.75492E-16	-5.11060E-18
16	9	1.31799E-18	-1.55638E-17	16	10	-3.24010E-19	-3.69527E-21	16	11	5.84217E-21	-6.03517E-20
16	12	1.64585E-21	-2.45595E-21	16	13	2.37411E-22	1.38418E-22	16	14	-5.19129E-24	-1.59612E-23
16	15	-3.17911E-24	7.53687E-26	15	16	-4.67554E-25	1.36546E-25	17	12	2.56127E-21	1.09106E-22
17	13	8.24181E-23	1.08015E-24	17	14	-3.62915E-24	6.16671E-24	18	12	1.65282E-22	1.20077E-22
18	13	4.87412E-24	-3.69401E-23	18	14	-2.25483E-25	-3.97434E-26	19	12	4.64057E-22	-5.71284E-23
19	13	1.53383E-23	-2.91541E-23	19	14	-1.30602E-25	-7.81936E-25	20	13	1.27350E-23	7.26916E-24
20	14	1.57393E-25	-2.28849E-25	21	13	6.00205E-25	-1.73520E-26	21	14	3.37218E-25	1.99486E-27
22	14	-2.51579E-26	8.25801E-26								

EARTH MODEL

SEMI MAJOR AXIS (METERS)	FLATTENING	GRAVITATIONAL CONSTANT (METERS**3/SECONDS**2)
6378155.00	1./298.255	3.986013000D 14

APPENDIX D

SOLAR FLUX VARIATION

SOLAR FLUX VARIATION

YYMMDD	Solar Flux Values	Magnetic Index
710331.	103.	19.
710401.	97.	12.
710402.	108.	7.
710403.	109.	19.
710404.	108.	27.
710405.	108.	11.
710406.	109.	12.
710407.	113.	7.
710408.	110.	6.
710409.	109.	43.
710410.	110.	23.
710411.	124.	24.
710412.	129.	10.
710413.	140.	8.
710414.	140.	22.
710415.	139.	33.
710416.	139.	13.
710417.	139.	6.
710418.	140.	9.
710419.	138.	8.
710420.	135.	5.
710421.	128.	11.
710422.	119.	13.
710423.	120.	8.
710424.	110.	2.
710425.	105.	1.
710426.	104.	4.
710427.	100.	8.
710428.	96.	16.
710429.	94.	12.
710430.	93.	10.
710501.	98.	7.
710502.	98.	17.
710503.	104.	8.
710504.	111.	8.
710505.	116.	8.
710506.	123.	35.
710507.	129.	29.
710508.	130.	15.
710509.	135.	11.
710510.	137.	9.
710511.	137.	5.
710512.	128.	3.
710513.	122.	4.
710514.	120.	15.
710515.	116.	12.
710516.	114.	5.
710517.	110.	19.
710518.	109.	33.
710519.	109.	10.
710520.	103.	5.
710521.	99.	4.
710522.	91.	5.